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AUDITORY SENSATION IN AN ELEMENTARY LABORATORY COURSE.

By PROFESSOR MAX MEYER, University of Missouri.

The following description of the manner in which I let my students perform certain experiments in an elementary laboratory course is offered to those of my colleagues who, like myself, might have found the corresponding recommendations of Titchener in his *Experimental Psychology* unsatisfactory, without, perhaps, seeing a way of improving upon them.

Whoever has attempted to teach an average student the most elementary facts of auditory sensation will readily concur in Titchener's statement that 'Sensations of tone are, perhaps, of all sensations, those which the average student approaches with the greatest diffidence and the least interest.' The problem before the instructor is, then, not merely *what* to teach, but even more *how* to teach it so that the diffidence of the student will be overcome and his interest awakened. Now, it seems to me that we cannot with certainty make a student confident and interested in some kind of work unless we insist from the start on his complete success in whatever experiment we tell him to perform. The student who merely pretends to have observed what he is expected to observe, is sure to lack confidence and interest in the next experiment he is told to take up. To insist upon success, however, is easier in theory than in practice. It is possible only if two conditions are fulfilled: 1. The problem set must not require a power of concentrating one's attention beyond the capacity of the student at the time. 2. The instructor must be able to convince himself, by other means than the student's mere assertion, that the student has actually observed the phenomenon in question. Let us now apply these conditions to the particular case.

Titchener devotes, rightly, I think, six pages exclusively to difference tones. Difference tones are certainly as interesting in themselves and as important for the theory of hearing as the phenomena of color contrast, *e. g.*, are in another field of sensation. When we read, however, the directions which Titchener gives to the student and the instructor, we must be struck by the fact that the above two conditions are not fulfilled.

1. The student is given two Quincke tubes and told to observe that, when sounded together, they produce an additional

tone which is a double octave lower than the lower primary tone, or, in another case, a single octave lower, or like the tone of a certain given third tube. Now, according to my experience with students, this is too difficult a task for the average student. He is expected to make up his mind whether he does or does not 'hear a tone' while the only characterization of that state of consciousness which his instructor calls 'hearing this tone' is the name 'lower double octave of the lower primary tone.' This means something to a musical student, a student who enters the laboratory with a considerable ability to concentrate his attention upon auditory phenomena. To the average—even piano-playing—student it amounts to practically the same as being told to think in a language which he never learned.

2. The instructor has no means of determining whether the student 'heard the tone' except the affirmative answer of the student. But this is at least as unreliable as a student's answer to the instructor's question, at the end of a lecture, whether the student understood the lecture. How reliable the answer is in this latter case, every teacher knows well enough. Therefore, instead of asking the above question, he will use other means of finding out what the student has learned. Should we not, in a laboratory course, too, use other means of finding out whether the student really observed what he is expected to observe?

Having had very good success with my methods of introducing the average student into observing difference tones, I wish to describe these methods here, in the hope that others, who might imitate them, will be equally successful with them.

I give to the student two whistles, either Galton whistles or Quincke tubes. The latter being particularly cheap, it might be best to speak of their use here, although Galton whistles are much easier to handle. I give to the student two Quincke tubes of rather high vibration frequency (not less than 2,000, the higher, the better), attached to a single mouth piece of glass by means of a short tin tube closed with cork stoppers of which one carries the mouth piece, the other the Quincke tubes. I show the student that it is easy to suppress either of the tones by covering the opening of the resonance tube with a small piece of writing paper. I further call the student's attention to the fact that he can make the tone of a sounding tube *lower* by narrowing the free end of the resonance tube by means of a small piece of wax. (It is best to put on a piece somewhat too large and to melt out gradually by means of a large, somewhat heated nail as much as is desired.) I now let the student listen successively to one and the other tone, calling his attention to the fact that both are very high and not very different.

I must say here, for the reader, that the difference of vibration rate may be about 200 or 300. I now let him sound both tubes simultaneously and call his attention to the rather low, humming tone, a tone so different from the primary tones that a student hardly ever fails to notice it immediately. This, however, is not the end of the first experiment, but only its beginning, merely a preliminary step. I now set before the student a definite task which it is within his power to perform. I give him a felt hammer and a tuning fork the vibration rate of which differs by 50 or 100 vibrations from the difference tone. I tell him that the difference tone is lower (or higher, as the case may be) than the tone of the tuning fork, but that it can be made equal to it by making the whistle tones more (or less) equal to each other. And then I leave him alone with the task of thus *tuning* the difference tone in unison with the fork tone. It is extraordinarily rare that a student does not succeed in this, although some take more time for it (perhaps one or even two hours) than others.

The reader will easily comprehend the advantages of the method just described. The difference tone is so different from the primary tones that even a student with a minimum ability to concentrate his attention upon tones notices it without difficulty. And then, what is even more important, the task of tuning this very difference tone compels him to concentrate his attention on the tone again and again for an hour or so. This is of the utmost importance because it trains him in sound analysis. It is extremely difficult for the instructor to train a student's ability to analyze a sound by simply telling him to try, try, try again and again, to convince the student that this is an effective way of acquiring this ability if he does not possess it. The student, as a rule, will not do it. Here, however, the mechanical task of tuning the whistle induces him again and again to do what the instructor wants him to do, to pay attention to a partial phenomenon, the difference tone produced, and induces him much more effectively than the instructor's mere advice. Still more important, however, is the fact that the instructor can easily tell if the student actually succeeded in observing the difference tone. He certainly could not by accident have *tuned* a tone correctly which he did not *distinctly hear*.

To give the student further training in what he needs so much, in the ability to direct his attention to partial sounds, I give him a bass bow and two tuning forks on resonance boxes, say of 450 and 525 vibrations, and instruct him in applying the bow to the *side of one* of the tines half an inch below the end. (I never use for this purpose the top surface of a tine, because bowing at the top surface is more difficult and tears the hair

out of the bow; besides, there is usually some tuning wax on the top surfaces of my forks, which would be ruinous to the bow.) I further give him a fork without resonance box, but with adjustable weights, ranging from about 60 to 90 vibrations, and tell him that the difference tone of the other two forks is identical with one of the tones of this fork. I then place the weights at one extreme and set before the student the task, not of merely listening to something, but of *doing* something, of tuning the adjustable fork in unison with the invariable difference tone. At the same time I use the opportunity of introducing him into another phenomenon by telling him that he will clearly hear beats when the tones approach each other, and that by making these beats slower and slower until they disappear he can obtain the greatest accuracy of tuning. When the student has succeeded, he calls the instructor who easily convinces himself as to whether the difference tone and its beats have been observed. With regard to the beats he can do this by slightly mistuning the fork and requesting the student to tap with his finger in the rhythm of the beats.

When the student has performed these two experiments he has acquired to a considerable degree what is an absolutely necessary condition for any work in auditory sensation, the ability voluntarily to direct his attention to a partial sound, an ability which so few students possess when they enter the psychological laboratory. I now feel justified in making him undertake work in which he must be practically without any aid or supervision on the part of the instructor. I give him a series of forks on resonance boxes representing the numbers from 1 to 12, say the forks 100, 200, 300, etc., up to 1,200, or the forks 75, 150, 225, etc., and tell him to verify for himself the most important laws concerning difference tones. These laws I give him in a preceding lecture, and I copy them below as I have previously published them. (*Zeitschrift*, 16, p. 2.)

It is essential for these experiments that the student be in possession of sources of sound which produce pure tones and can be tuned in definite intervals with the utmost accuracy, since otherwise the observations would be too difficult at this stage of the student's training. Therefore I should not use for these experiments sources of sound other than good tuning forks on resonance boxes. It is further advantageous now to make two students work together. In the preceding experiments one could do the work as well alone. But here, since it is well to bow the forks in quick succession in order to obtain two equally strong tones, and since it is usually necessary for the observer to find a place where the difference tone is strongest, sometimes near the resonance boxes, sometimes in a particular position to the walls of the room,—the bowing of the forks should be done

by an E student and the O student be left free to concentrate his full attention on the observation.

The laws which the student is to verify for himself, do *not* express *all* the difference tones which one might possibly hear in every possible combination of objective tones, but merely those difference tones which one is *most likely* to hear in those combinations which correspond to relatively simple ratios of the vibration rates and are therefore (musically and otherwise) *particularly interesting*. These laws are the following four:

1. In case the ratio of the vibration rates does not differ much from 1:1, say in 11:12, or in 9911:9989, a single difference tone is audible, whose pitch corresponds to the pitch of a tuning fork the vibration rate of which is equal to the difference of the vibration rates of our case. In addition to the difference tone, however, beats are usually clearly audible, and a 'mean tone' is audible too, which lies between the two primary tones. If the interval is quite small, this mean tone is usually more pronounced than either of the primary tones, particularly when we hear with one ear only, having the other ear plugged. The beats just mentioned seem to be the fluctuations of the intensity of the mean tone rather than of the primary tones, if we use one ear only.

2. A second class of ratios which is of particular interest, is that of the ratios whose numbers differ by 1. In each of these cases the difference tone 1 is audible, but often quite a number of additional difference tones can be perceived. If the numbers of the ratio are rather small, as in the case—5:4, all the tones from 5 down to 1 are without any great difficulty noticeable. As we study ratios of increasing numbers, the tones following directly upon 1 (in a rising direction, of course) seem to have a tendency to drop out. And if we go on in the same way, we soon find only one difference tone left, the tone 1. We have then simply reached a case in which the difference tone is determined by the first law above. The accompanying table represents this class of ratios with their difference tones.

Obj. Tones	Diff. Tones easily audible
2, 1	—
3, 2	1.
4, 3	2, 1.
5, 4	3, 2, 1.
6, 5	4, 3, ?, 1.
7, 6	5, 4, ?, 1.
8, 7	6, 5, ?, 1.
9, 8	7, 6, 5, ?, 1.
10, 9	?, 1.

3 A third class of ratios to be studied are the ratios made

up of comparatively small numbers, representing intervals less than an octave. In these cases three difference tones are often easily noticeable, one corresponding to the direct difference of the vibration rates ($u-1$); one corresponding to the difference between the latter number ($u-1$) and the vibration rate (1) of the lower primary tone, *i. e.*, ($21-u$); and one corresponding to the difference between the just mentioned differences ($u-1$) and ($21-u$), *i. e.*, ($2u-31$). It is to be noticed, however, that a difference tone is hardly ever audible which corresponds to a difference *larger* than the subtrahend; for example, the primary tones 9 and 5 produce the difference tones 4 and 1, but not $3=4-1$, or at least not an easily noticeable tone 3, 3 being larger than 1. The following table contains a few examples of this class:

Obj. Tones	Difference Tones
8, 5	3, 2, 1.
5, 3	2, 1.
9, 5	4, 1.
7, 4	3, 1.
11, 7	4, 3, 1.

4. The fourth class to be studied are the ratios made up of comparatively small numbers, representing intervals larger than an octave. The first fact to be noticed here is the lack of a difference tone corresponding to the direct difference of the two vibration rates. Such a tone, if audible, would lie between the primary tones. As a rule, only one difference tone is easily noticeable in these cases, which can be found according to the following rule: Find the *smallest* difference between the larger number of the ratio and any multiple of the smaller number. The table contains a few instances of this class:

Obj. Tones	Difference Tone
11, 4	$1=3 \times 4 - 11$.
12, 5	$2=12 - 2 \times 5$.
9, 4	$1=9 - 2 \times 4$.
11, 3	$1=4 \times 3 - 11$.
5, 2	$1=5 - 2 \times 2$.
8, 3	$1=3 \times 3 - 8$.

When the student has faithfully done this work, he has a fairly good idea of the laws of tone perception so far as difference tones are concerned, and a considerable ability to control his attention in auditory observation. But I wish to give him further training. To accomplish this without having to fear a decrease of interest on the student's part, I give him a practical problem the solution of which does not merely require him to listen, but again to *do* something. I tell him that to be

familiar with difference tones is not only of theoretical, but also of practical importance, that one may apply such a knowledge to the problem of tuning an organ according to a prearranged plan. I now place him before my experimental organ (a reed organ with two manuals, the tones of the upper manual differing from those of the lower, described in *Zeitschrift*, 33, p. 292) and tell him to determine by means of difference tones the exact vibration rate for each key. The data which I give him are: 1. the fact that one of the f 's has the vibration rate 1024 (it does not really have this vibration rate, but it makes the computation easier, without, of course, changing the ratios), and 2. the fact that when the vibration rate for any key has been found, those of its octaves are determined by either dividing or multiplying by 2. I further advise him to use exclusively the lowest difference tone audible, and never to use the difference tone of a combination representing an interval larger than a Fourth, because in larger intervals the lowest difference tone does not correspond to the direct difference of the vibration rates. Now and then helping him a little, I make him find out all the vibration rates and *ratios* on my organ. For example, he combines $f=1024$ with the next higher a and finds by pressing down other keys and comparing that the difference tone is the f two octaves below. He knows then that the unknown a is equal to 1024 plus one-fourth of 1024, that is 1280. Or, having found b equal to 1440, he combines it with the following c and finds that the difference tone is four octaves below this c . He then finds the vibration rate of c from the equation

$$c = 1440 + \frac{c}{19}.$$

Thus I give the student, not only further training in sound analysis (the average student cannot have too much of it!), but also an introduction into the musical significance of the different ratios. Titchener introduces the student into this matter on pp. 32 and 33 by means of two tables, a picture of a key-board, and the necessary explanations in words. However excellent this brief introduction of Titchener may be, I doubt if any student derives much benefit from it. The student is certainly far more familiar with the relations existing between vibration rates and their ratios on the one hand, and the keys of a key-board on the other, if he has found these ratios by his own labor, working on the instrument itself and solving a practical problem the possibility of the solution of which with no other help than his own ear never entered his mind.

Only now should I recommend to have the student work on overtones. These are far more difficult to observe than difference tones. But after such a considerable training in sound analysis as described above the student is able to convince him-

self without too much difficulty of the existence of overtones and their significance for what the organ builder (and I with him, in opposition to Titchener¹) would call 'quality' of a tone.

Concerning 'summation tones' I do not tell my students anything in an elementary laboratory course, since I do not regard them as being of any direct importance to the psychologist.²

There are only two further classes of experiments on auditory sensation which I prescribe to my students: 1. Experiments on noise. 2. Experiments on the briefest stimulus producing a tone. The experiments on noise are done by us in about the same manner as recommended by Titchener, except that I do not tell my students that tones and noises are two fundamentally distinct classes. The experiments on the briefest stimulus are performed in this way. I give the student an 18 inch disk (of zinc or aluminum) with 150 holes, a rotation apparatus, and a support with rubber tube and two end pieces of glass for blowing, further a tuning fork of, say, 600 vibrations and a felt hammer. O has to blow and observe, E to increase very gradually and constantly the speed of rotation and to observe to the extent he can. O now and then sounds the tuning fork very briefly and compares its tone with the tone of the siren disk. When the tone of the latter has become equal to the siren tone, he stops the experiment. I have devised this form of the experiment in order to be sure that a 'tone' is heard produced by the siren. If it were not a 'tone,' it could not be said to have risen to unison with the fork. Of course, in the above case no one would doubt the existence of a real tone sensation; but one might doubt it in the following modifications of the experiment. The student glues a paper ring over the holes, leaving only 6 or 7 consecutive ones open. The experiment is repeated. Instead of a continuous tone, a series of tones of very short duration is observed. In every other respect the experiment is the same as above. Now a further hole is closed by a piece of paper. The observation is more difficult, but the result is the same, a tone is audible. Another hole is closed, and so on, until only two holes are open. The student observes that the tone decreases in intensity while the number of holes approaches 2, since in all our sense organs the sensation does not possess its full intensity at the very time when the stimulus begins to act, but has to rise to it. This natural rise is impossible when the stimulus is extremely shortened. This decrease in intensity together with the noise accompanying each blow of a hole is responsible for the increasing

¹See my article on 'The Attributes of the Sensations,' *Psychol. Review*, II, 1904.

²See my article 'Ueber Kombinations- und Asymmetrietöne,' *Annalen der Physik* (Vierte Folge) 12, 1903.

difficulty of observation. However, the student is able to observe thus a tone even when only two holes are open, because he begins the experiment with an easy case and is given a chance to develop his power of observation as the difficulty of observation increases. Finally, the student leaves only one hole open, in which case an increase of the speed of rotation does not lead to any similarity between the siren sound and the fork tone which might be called unison. *I. e.*, the ends of the auditory nerve fibres need not receive more than two shocks to give rise to a sensation of tone. (The noise we hear is the result of irregular reflections of each single puff.)

SUMMARY.

The following experiments are recommended in the order in which they are enumerated and in the manner described above:

1. Tune a difference tone to unison with a fork.
2. Tune a fork to unison with a difference tone. Observe the beats.
3. Observe the difference tones of as great as possible a number of combinations of two objective tones each.
4. Apply your knowledge of the difference tones to the problem of tuning an organ.
5. Observe overtones and 'quality of tone.'
6. What is a noise? Produce noises by divers means and explain them.
7. How many shocks of the nerve ends are necessary to produce a sensation of tone? (Siren experiment.)